An Advanced Control of Grid Connected Wind Turbine Generators for Enhancement of Low-Voltage Ride-Through Capability

著者	AUNG KO THET
号	56
学位授与機関	Tohoku University
学位授与番号	工博第4587号
URL	http://hdl.handle.net/10097/61982

	あうん こうてっと
氏　　　　　名	AUNG　KO THET
授　与　学　位	博士（工学）
学位授与年月日	平成２４年３月２７日
学位授与の根拠法規	学位規則第４条第１項
研究科，専攻の名称	東北大学大学院工学研究科（博士課程）電気・通信工学専攻
学位論文題目	An Advanced Control of Grid Connected Wind Turbine Generators for Enhancement of Low-Voltage Ride-Through Capability （電力系統の瞬時電圧低下時における風力発電機の連系運転継続能力向上制御）
指　導　教　員	東北大学教授　斎藤　浩海
論文審査委員	主査　東北大学教授　斎藤　浩海　東北大学教授　一ノ倉　理 東北大学教授　石黒　章夫

論文内容要旨

One of the major concerns for the stability of electric power systems including large amount of WTGs is how to improve the LVRT capability of WTG during grid disturbances. This doctoral dissertation addresses an advanced control method for the Low-Voltage Ride-Through (LVRT) of wind turbine generators (WTGs); i.e. continuity of the wind power generation under faulted condition in electrical power transmission network. In this dissertation, we propose a new pitch angle control and a Power Curtailment (PC) control for LVRT capability improvement of fixed-speed wind turbine (FSWT) and the variable-speed wind turbine (VSWT) in wind farm, respectively. The proposed method adjusts the pitch angle in the FSWT and, adjusts the pitch angle and modulation of converter in VSWT. The effectiveness of the proposed method is confirmed by simulation studies.

Chapter 1 Introduction

This chapter introduces the background of wind power integration with respect to the stability of power system and objective of research. The fundamental characteristics of modern electric power systems are described. Basically, the stability, the reliability and the secure operation of modern power systems depend on the network configuration, protection relay system, and the operation and control of conventional power plants. At low penetration level of wind power, the impact of wind farms is not the system wide concerns. At high penetration level, if a large numbers of wind power generators replace the conventional power plants, the concerns about the power system stability increase; such as the deviations in power system frequency due to the unscheduled disconnection of a large numbers of WTGs following the disturbance. Therefore, WTGs are demanded more controllability to fulfill the grid codes, such as LVRT requirements. The characteristics of LVRT requirements in European countries with large wind power penetration are also presented.

Chapter 2 State-of-the-Art in Mitigating the Impacts of Wind Power Integration into Power Systems

This chapter describes the state-of-the-art in mitigating the wind power impacts on the operation of power system. In this chapter, the literature review in the experiences of power system operation with large wind farm integration, the concerns to the power systems energy balancing and transient stability are included. The impacts of wind energy depend on 1) the level of wind power penetration, 2) grid size and 3) generation mix of the power systems. Wind power integration at low to moderate levels is a matter of cost. For high level of wind power integration, the ability to maintain the system stability is concerned. One of the major concerns in power system operation is the stability which deals with the behavior of the power system to remain in a state of operating equilibrium under normal operating conditions and to regain an acceptable state of equilibrium after being subjected to disturbances. To maintain stability, the appropriate power injection and network voltage reestablishment are required in the event of disturbance, which are contributed by the conventional power plants. For power system with large wind power penetration, the roles of conventional power plants are replaced by WTGs. Therefore, WTGs must contribute the system stability by remaining connected to the power system in the event of grid disturbance. According to the experience from European countries, the unscheduled disconnection of wind energy generation is not undesirable to maintain the demand-supply balance. Therefore, LVRT requirement becomes one of the essential grid codes in interconnection of wind farm. The characteristics of LVRT requirements of each country are different from others due to the differences in voltage level of interconnection, size of wind farm, generation mix and system operation practices. Due to the expectation of large wind power integration in Japan, WTGs with LVRT capability also becomes important in near future.

Chapter 3 Proposal of Pitch Angle Control based on Fast-Response Voltage Dip Detection

This chapter addresses the concept and details of proposed pitch-angle control in the FSWT. FSWT is based on a directly grid-coupled Squirrel-Cage Induction Generator (SCIG) which absorbs reactive power from the power grid. This implies that the SCIG is excited from the power grid and cannot control their excitation by themselves. Due to the lacks of self-excitation control, SCIG is usually equipped with capacitors for reactive power compensation. However, the use of these capacitors is not enough to enhance the LVRT. During the voltage depression caused by a fault, the wind turbine is only able to deliver real power to the network in proportion to the retained voltage. The difference between mechanical power supplied by the rotor and electrical power output of the generator will appear as acceleration power and then speeding up the rotor. The rotor over-speeding will cause the disconnection of WTG to avoid damage. Therefore, it is necessary to suppress the WTG's rotor over-speeding to remain connected with power system.

Figure 1 shows the concept of the proposed pitch control. The main concept of the proposed pitch angle control is based on the voltage dip detection by fast response of under voltage relay and a Proportional-Integral (PI) control of terminal voltage, V_s, during voltage dip. A sudden voltage dip is detected by the under voltage relay to initiate the pitch angle control in LVRT mode. Then, the pitch angle of blades is changed according to the depth of voltage dip so as to suppress the rapid increase of rotor speed, ω_{rotor}, and stator current, I_s, by the release of blowing wind power. By this way, the mechanical input power, T_{wt}, can be controlled in order to balance the retarding electrical torque, T_e, of the generator during and after the fault.

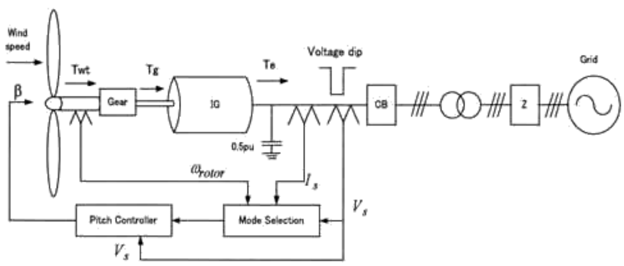

Fig. 1. Concept of proposed pitch controller for WTG

Figure 2 shows a block diagram of the proposed pitch control which consists of 3 parts: 1) wind turbine protection and pitch angle controller selection, 2) LVRT mode controller, and 3) normal mode controller. In the first part, the protection relays for the rotor over speed and induction generator over current protection are included. Either over speed limit (1.1 p.u.) or over current limit (2 p.u.) is detected, whether in LVRT mode or normal mode, WTG is disconnected. The second part enclosed by the dotted lines is designed to control the pitch angle according to the voltage dip. The pitch angle β_{LVRT} for LVRT is the output of PI controller whose input is the difference between reference voltage, V_{ref}, and the measurement of generator terminal voltage, V_s. When the generator terminal voltage drops below the 0.7 (p.u.) of nominal voltage, the LVRT pitch control mode is activated by the under voltage relay with the total delay time of 100ms. It is assumed that this delay time includes the relay pickup time, Tpick<100ms, communication and switching delay. After the monitored voltage, Vs, has recovered for more than 5s, LVRT pitch control mode is deactivated. During the normal mode operation which is determined by the protection system switching logic, the pitch angle is controlled by conventional controller in which generated active power, P_e, is used as an input parameter. When the generated active power is above the rated power, 2MW, the blades are pitched by βNORMAL to reduce the extracted wind power.

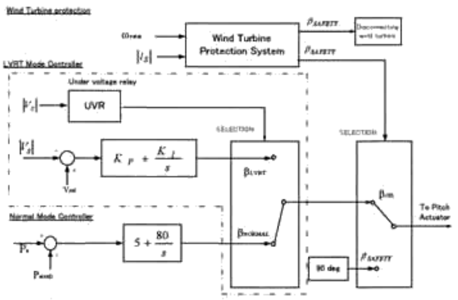

Fig. 2. A block diagram of the proposed pitch control

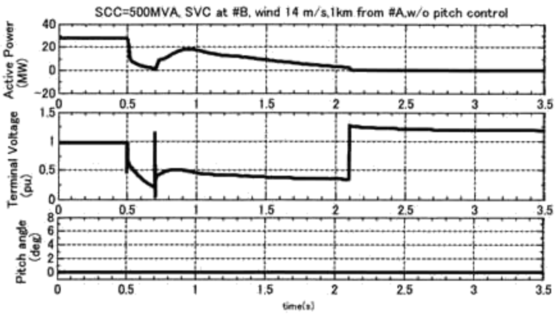

Fig. 3. Wind Farm Behavior (without pitch control)

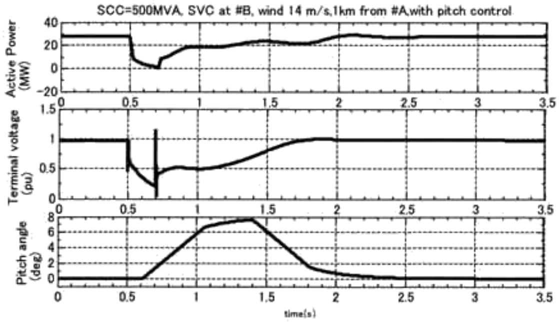

Fig. 4. Wind Farm Behavior (with pitch control)

The effectiveness of the proposed pitch control is verified by using simulation tools of Matlab/Simulink. A power system model with the wind farm of 30MW installed capacity and Static Var Compensator (SVC) was used in simulation studies. In the simulation studies, as we neglect the configuration of wind farm internal network, aggregated wind farm model is used by representation of 15 WTGs of 2MW rating each into a single wind turbine model. As the voltage dip duration is relatively short and the maximum output power generation is the worst case in LVRT studies, the use of rated wind speed is appropriate. Three phase line to ground fault occurring for 200 ms at one of the double circuited transmission network with the voltage level of 66kV is considered in simulation study. The simulation results of wind farm behavior are shown in figure 3 and 4, respectively. These results show that the proposed pitch control is effective to improve the LVRT of wind farm with FSWT.

Chapter 4 Performance of Proposed Pitch Control in Fixed-Speed Wind-Turbine Generator with Induction Generator

In this chapter, the performance of proposed pitch control is confirmed by considering the influence of Short Circuit Capacity (SCC), difference locations of fault and reactive power source. The simulation results of wind farm behavior show that the proposed pitch control is effective to improve the LVRT under different SCC with appropriate reactive power source location and can be applicable in real power systems. The LVRT capability can be improved in some specific wind speed at which the use of SVC cannot improve. The range of proportional gain in a proposal with respect to the response time of under voltage relay is presented. Moreover, performance of the proposed pitch control is compared with other possible approach in which the rotational speed of rotor is used as a feedback controller. Comparing to the approach of rotational speed feedback, the proposed method can give better results in network voltage recovery.

Chapter 5 Power Curtailment Control in Variable-Speed Wind-Turbine Generator with PMSG

This chapter presents a new control method to mitigate a faulted network impact on PMSG based VSWT. This type of VSWT uses a full scale of back-to back frequency converter to connect the network, as shown in figure 5. A Power Curtailment (PC) control is proposed to react rapidly to the voltage dip. The outline of PC control for LVRT of PMSG wind turbine is shown in figure 5 by red dotted line. The main idea of proposed control is to release the extracted wind power by means of pitch angle (β) control and active power control (P_{ref}) at generator side converter. When the voltage dip (Vpcc) is occurred at the Point of Common Coupling (PCC), the injected power to power systems (P_l) is decreased according to the voltage dip. To improve the LVRT capability of PMSG, it is necessary to maintain the balance between generated power (P_G) and injected power to power systems (P_l) during the voltage dip. If not, the power imbalance will cause the voltage (E_{dc}) raise in DC link. This will cause the operation of

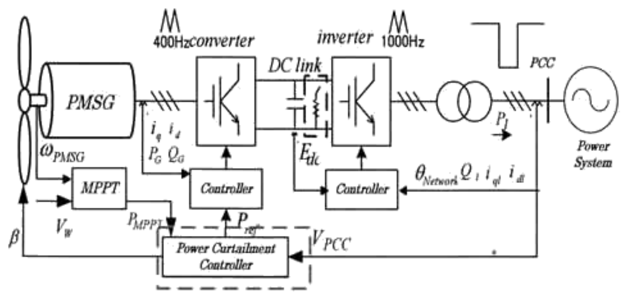

Fig. 5. Concept of proposed PC control in PMSG

protection system to protect the power electronic devices. In the PC control, the mechanical input power from wind is controlled by means of pitch angle (β) and generated electrical power (PG) is controlled by generator side converter.

In figure 6, the block diagram of PC control is illustrated. There are three portions in figure 6; 1) PC control, 2) Converter Control, and 3) Pitch Actuator. The aim of the converter control is to set the generator terminal voltage according to the active power (P_G) and reactive power (Q_G) of PMSG. The converter also controls to achieve the zero reactive power absorption or generation by PMSG. When the voltage at the PCC is detected to <0.9 (p.u.), PC control switches the active power reference (P_{ref}) to the 0.4MW, i.e., 20 percent of P_{rated} as the voltage at PCC is dropped to 0.2 p.u. The value of P_{ref}, is also used as the control reference of pitch angle control. For normal condition, converter and pitch actuator are controlled by means of P_{ref} set by the Maximum Power Point Tracking (MPPT) algorithm.

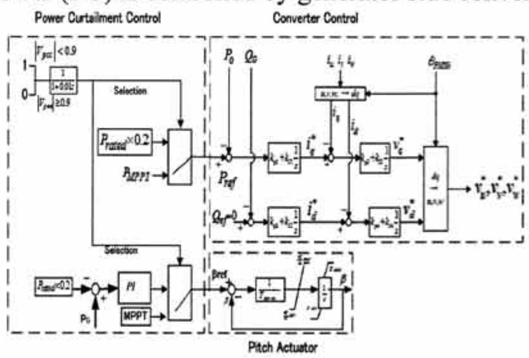

Fig. 6. Block diagram of power curtailment control

The effectiveness of the new control method is verified by simulation study in which the behavior of PMSG under faulted conditions is analyzed. Three phase line to ground fault occurring for 200 ms at one of the double circuited transmission network with the voltage level of 66kV is considered in simulation study. We also consider the influence of SCC and particularly paid attention to behavior of E_{dc}. Comparison study between the use of traditional approach of using the braking resistor parallel to DC-link; as shown in figure 5 enclosed by black dotted line, and the proposed PC control is also carried out. As shown in figure 7, the PC control can reduce the over voltage in DC-link so as to improve the LVRT capability of PMSG.

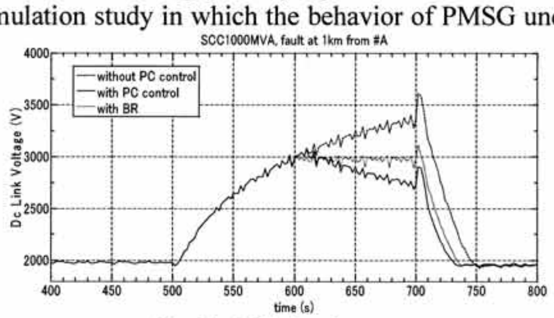

Fig. 7. DC link voltage

Chapter 6 Summary and Conclusion Remarks

This chapter summarizes the dissertation's main points and contributions. Moreover, future aspects of research are proposed. Based on the type of wind energy generation systems, this dissertation can be categorized into two parts. In the first part, we use FSWT model including a SCIG. As the LVRT behavior is related to short-term transient stability, we used the instantaneous time domain models of wind turbine generators and three-phase power transmission network which are relevant to the phenomenon of short-term transients. In the second part, we use VSWT model including a PMSG. In order to analyze the LVRT behavior, the instantaneous time domain models of PMSG, converter, inverter and three-phase power transmission network are used. The simulation results shown in both parts confirmed that the LVRT requirements can be achieved by the proposed control method. In the case of FSWT, it is obvious that the proposed control method can mitigate the impact on the system voltage; improvement of voltage recovery during the post fault period. However, the proposed control method is based on the feed-forward control method approach which has disadvantage in output power oscillations during the post-fault period. According to the power system size and generation mix, there is a possibility to propagate through the system causing synchronous generator to exhibit speed oscillations. In the case of VSWT, confirmation of proposed control method with Doubly Fed Induction Generator (DFIG) is not yet included. Moreover, the phenomenon of the rising inrush current in power electronic devices and blocking the inverter/converter are not considered as they are not included in the scope of this study. There are many ways to improve proposed method presented in this dissertation as follows:

1) Improvement in control method with respect to the operation states of wind farm and power systems.
2) Detailed design approach of control system to get the least output power oscillations during the post-fault period.
3) Consideration of detailed wind farm structure.
4) The study for unbalance fault condition.

論文審査結果の要旨

風力発電機は地球温暖化ガスを排出しないクリーンな電源として世界的に普及してきており、電力系統への連系台数はさらに増大していくと予想されている。風力発電機の連系台数が増大したときに最も重要となる問題は、系統事故による瞬時電圧低下時において、多数の風力発電機が出力低下により加速し、回転速度の超過や発電機の過電流により遮断器が動作して、電力系統から自ら切り離れてしまうことである（以下、解列と呼ぶ）。その結果、電力不足が生じ、電力系統全体の需給平衡が崩れ、周波数が不安定化して、最悪の場合は広域停電を招く危険性がある。著者は、瞬時電圧低下時の風力発電機の制御方法について種々検討を行い、風力発電機が系統から解列しないための連系運転継続能力（Low-Voltage Ride-Through, LVRT）を向上させる制御方法を明らかにした。本論文はこれらの成果をまとめたものであり、全篇 6 章よりなる。

第 1 章は序論である。

第 2 章では、瞬時電圧低下時における多数の風力発電機の解列が、電力系統全体の需給不平衡と周波数の不安定化を招く原因になることを論じ、風力発電機自身に LVRT 能力を備えることの重要性を指摘している。

第 3 章では、誘導機を用いた固定速風力発電機の LVRT 能力向上制御として、風車の翼のピッチ角度を発電機端子電圧の低下量に合わせて調節し、風車の回転速度超過と誘導機の過電流を抑制することにより風力発電機の解列を防ぐ新しい制御方法を提案している。提案手法を電力系統に連系した風力発電機群の縮約モデルに適用し、その詳細なシミュレーションを行った結果、提案手法は有効な制御方法になり得ることが明らかになった。これは固定速風力発電機の LVRT 能力を向上させる上で注目に値する成果である。

第 4 章では、電力系統の短絡容量、電圧調整装置（SVC）の設置箇所、事故発生位置、風速のそれぞれが、前章で提案した LVRT 能力向上制御の性能に及ぼす影響について検討を行い、提案手法が種々の系統状況において有効であることを示している。さらに、提案手法の有効性が瞬時電圧低下を検出する不足電圧リレーの動作遅れ時間に影響を受けること、また、その動作遅れ時間に応じた最適制御ゲインの範囲が存在することを明らかにしている。これらの結果は提案手法の実用化に有用な知見を与えるものである。

第 5 章では、永久磁石同期発電機を用いた可変速風力発電機の LVRT 能力向上制御として、発電機端子電圧の低下量に合わせて発電機有効電力出力を調節するのと同時に風車の翼のピッチ角度も調節することで、解列を避ける方法を提案している。計算機シミュレーションにより、従来対策法の制動抵抗を使用する方法と比較した結果、従来法と同等以上の効果が得られることが明らかになった。これは可変速風力発電機の LVRT 能力をさらに向上させる上で有用な知見である。

第 6 章は結論である。

以上要するに本論文は、多数の風力発電機が連系された電力系統における風力発電機の制御方法について検討を行い、瞬時電圧低下という厳しい条件下においても系統の需給平衡と周波数安定化を実現するための LVRT 能力向上制御を提案したものであり、電力システム工学の発展に寄与するところが少なくない。

よって、本論文は博士(工学)の学位論文として合格と認める。